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Planning safe distances between workers on construction sites

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ABSTRACT

A planning methodology is introduced to ensure that workers on construction sites remain at a safe distance from each other. The methodology is based on the assumption that hazardous conditions, which occur on sites due to the proximity of different workers, depend on the interaction between both reinforcing and counteracting characteristics of the workers. The methodology includes a matrix-based method for the definition of minimum safe distances between workers, and the use of 3D time–space diagrams to represent and analyze the dynamic movements of workers on site. The methodology is implemented in a real case study in order to verify its feasibility.

1. Introduction

According to conservative estimates, at least 60,000 people are fatally injured on building sites around the world every year [7]. Many hundreds of thousands more suffer serious injuries and ill-health. Worldwide, construction workers are three times more likely to be killed and twice as likely to be injured as workers in other occupations [3]. While fatal work injuries in the private construction sector in the US increased by 5 percent in 2012, this followed five consecutive years of declining fatal injury counts [14]. In the UK, the number of worker deaths in 2012/13 was 18% lower than the average for the past five years [6]. Although the statistics may show some improvement, they also clearly indicate that safety on construction sites remains a major problem.

Workers on construction sites are exposed to hazards that have three main sources: a) the work technology (e.g. the tools and equipment used to carry out the activity), b) the physical conditions (e.g. high elevations) and c) surrounding activities that are simultaneously carried out by other workers nearby [13]. This research focuses on the prevention of hazards of the third type: i.e. those created by surrounding activities. While there are many methods and models available to assess the risks that workers' own activities pose to themselves, few studies have dealt with the hazards derived from the activities of other workers on site to which workers are also frequently exposed [24].

The problem of accidents on construction sites that are caused by an excessive proximity between workers carrying out different activities is exacerbated by the fact that construction sites are dynamic: the location of workers is transient, and the physical structure and activities often change. Such accidents could be prevented by carefully planning and monitoring the location of workers on site while they perform activities, so that they can maintain a safe distance from other workers or their equipment at all times. However, in order to achieve this one needs to establish how such safe distances should be defined in the first place. Furthermore, one needs to provide managers with the tools to plan the construction activities accordingly. These tools should take into account the fact that both workers and equipment frequently change location.

The objective of this research is to develop a methodology that supports planning the dynamic locations of workers on construction sites, in order to prevent hazards that occur due to an excessive proximity between different workers. This paper will continue in Section 2 with a review of existing models and previous research. The third section presents the methodology that was developed in this research, and describes its application. Section 4 presents the results of an implementation of the methodology in a real-life case study, which was carried out to evaluate its feasibility.

2. Literature review

2.1. General construction safety planning tools and models

A significant number of studies have been carried out to develop tools and models for the planning of safe construction sites. Rozenfeld et al. [16] developed a Construction Job Safety Analysis tool, which focused on the identification of potential loss of-control events for a detailed planning of construction activities, based on data collected through interviews. Mitropoulos et al. [13] presented a model of the factors affecting the likelihood of accidents during a construction activity. The model focuses on the characteristics of a project that generate hazardous situations and shape actual work behaviors, and analyzes the conditions that trigger the release of the hazards. Saurin et al. [19] defined a Safety Planning and Control Model that includes three

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hierarchical levels, for long-, medium-, and short-term safety planning. Proactive and reactive performance indicators were defined for safety control and evaluation, based on the percentage of safe work packages and actual accident data. Jannadi and Almishari [8] developed a risk assessor model for determining the risk associated with a particular activity and the justification factor for a proposed response action. Tam et al. [21] developed a Non-Structural Fuzzy Decision Support System to evaluate safety management systems and prioritize safety improvement measures with the consideration of various decisions. Yi and Langford [24] analyzed historical safety records, and presented a model for estimating the risk distribution of a project and adjusting the project schedule to reduce risk. Hadikusumo and Rowlinson [4] developed a design-for-safety-process tool, aimed at capturing safety knowledge from safety engineers about construction safety hazards and the safety measures required.

These tools and models can provide valuable general information for safety planning, through the analysis of the causes of accidents and historical data. They are, however, neither sufficient for fully analyzing the likely locations and timings of accidents on a specific site, nor can they take into account the results of the interaction between two individual workers with different characteristics, which might create safety risks.

2.2. General work space allocation tools and models

A number of models have been developed for the allocation of the space required for activities on construction sites. Some of these models also take into account safety hazards. Riley and Sanvido [15] developed a manual space planning method that provided a logical order and priority for space planning decisions. The model allowed planners to identify potential spatial conflicts. Shaked and Warszawski [20] developed a knowledge-based expert system for work space allocation, which differentiates between horizontal zones (floors) and vertical zones (elevator shafts, staircases, piping shafts, and exterior facades). Akinci et al. [1] developed a model for automatically detecting conflicts between activities in four dimensions, categorizing these conflicts according to a taxonomy of time–space conflicts, and prioritizing the spatial conflicts detected. Winch and North [23] developed a decision support tool for marking up available space on site, allocating activities to spaces, and analyzing and optimizing space allocation in relation to the critical path.

While all these tools and models address the need to allocate site space for activities according to the specific conditions and schedule of the project, they do not fully address safety considerations by taking into account the characteristics of individual workers. Moreover, most of these models (the pioneering study by Riley and Sanvido [15] is a notable exception) focus on the definition of a static space for the execution of each specific task, which usually surrounds the component constructed in this task. Thus, they do not fully take into account the workers' movements on the site, (e.g. for fetching materials and removing waste).

2.3. 4D safety planning systems

A number of safety planning systems have been developed that take into account the spatial location of activities on site. Benjaoran and Bhokha [2] developed an integrated system for construction and safety management, which includes a 4D CAD model and a rule-based system that automates the hazard identification process. The rule-based system also suggests proper safety measures, including safety activities or requirements. Sacks et al. [18] developed a method for generating a set of possible loss-of-control scenarios for each planned activity in a given project, based on the likely locations of workers. A set of algorithms is then used to compute the probability of potential victims to be exposed to the loss-of-control scenarios. Zhang et al. [25] developed a rule-based safety checking system for the automatic identification of hazards that appear as the building is constructed, identifying their location in a Building Information Model, and providing solutions to mitigate the hazards. The proposed framework was implemented for the prevention of falling-from-heights accidents. Kang et al. [11] linked a 4D model with risk data to visualize the risks in each activity. Their system considers construction cost, duration and safety as risk factors.

All these systems take into account the spatial location of activities on the site to enhance worker safety. However, they do not deal directly with planning the location of workers on the site to ensure that safe distances are kept between different workers, as the present research does.

3. The proposed methodology

The objective of this research is to define a methodology that can reduce the hazardous conditions that occur on construction sites due to an excessive proximity between different workers. This study focuses on the proximity between workers, in addition to their proximity to equipment or dangerous materials on site, since workers often carry out their work in a dynamic and complex way that is difficult to model. Furthermore, this problem has not been sufficiently addressed in previous research.

This research is based on the assumption that hazardous conditions, which occur on sites due to the proximity of two workers carrying out different activities, are a product of the interaction between both reinforcing and counteracting characteristics of the workers. Such characteristics affect the probability that an accident will occur, and depend both on the activity carried out by a worker, as well as on the worker's individual attributes. For example, the risk of a welder accidentally causing a fire that injures another worker also depends on the degree of flammability of the materials used by the other worker, such as oil or paint. In other words, the level of risk depends not only on the severity of the hazard created by a reinforcing characteristic of one worker, but also on the degree to which a characteristic of the second worker counteracts this hazard. The implication of this is that not all workers need to be kept at the same distance from the area in which a certain activity is being carried out.

Prior to the application of the methodology, a preliminary stage involves an analysis of the planned processes on the site and the identification of the risks involved. After this preliminary stage, the model is applied in two stages:

1. Definition of required minimum distances between workers, using a matrix-based tool
2. Analyzing the planned movements of workers on site, using 3D time–space diagrams.

After the model is applied, the manager can implement controlling actions and approve a safe construction plan (Fig. 1).

3.1. Process analysis and risk identification

The preliminary stage of the application of the model involves a structured Preliminary Hazard Analysis (PHA) of the planned processes on site, which is followed by a detailed Job Safety Analysis (JSA) to identify the risks that are involved in specific activities within these processes. In line with the research objective, both PHA and JSA are focused on the hazards and risks to which workers are exposed because of surrounding activities. The input for this stage includes the existing construction plan for the project, which includes the scheduled activities.

The objective of the PHA is to identify the hazards that might be created by the processes that are planned to be carried out on site. The PHA involves a systematic survey of all the processes in the existing construction plan, and of the activities, resources and site space that these processes require, to identify the hazards that they might consequently involve.

A more detailed JSA is then carried out of those activities for which hazards were identified in the PHA. The JSA is carried out by breaking the activity down into a sequence of individual steps that are simple, continuous and clearly identifiable. The JSA provides decision-makers